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Design of Terahertz Waveguide Filters For Hybrid Manufacturing Based On CNC Milling and Laser Micro-Machining

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Abstract

This paper presents the design of terahertz waveguide filters, operating in the WR-3 frequency range of 220-325 GHz, which are ideally suited to a hybrid manufacturing platform. The platform considered in this research combines the capabilities of CNC milling and laser micro-machining to produce components that incorporate meso and micro scale features. The functional filtering features of the waveguide devices are micro size and require a higher dimensional accuracy and good surface integrity. Therefore, these features were designed for laser micro-machining with a dimensional accuracy better than 10 µm. At the same time other features used to assemble the device were made sufficiently large, meso scale, and thus to produce them using CNC milling with much higher material removing rates. By designing THz waveguide filter that incorporate micro and meso scale features it was possible to combine the capabilities of these two technologies and reduce the production time significantly while a higher resolution and dimensional accuracy was achieved for the filter structure. The design for manufacturing analysis of a WR-3 4th-order filter was carried by using a 2nd-order filter to demonstrate and assess the advantages of applying a hybrid manufacturing approach for its production. In particular, to validate the design, the 2nd-order filter was fabricated from a copper workpiece and its microwave performance was assessed. The results showed a relatively good agreement with the simulation results. Several factors which may impact the filter's microwave performance were identified and discussed. The feasibility study demonstrated the suitability of the proposed filter structure for hybrid manufacturing of small to medium size batches of THz waveguide devices with high design flexibility.

Keywords: laser micro-machining, waveguide, filter, terahertz

1. Introduction

There is an increasing interest in millimetre-wave (mm-wave) and terahertz components operating in the frequency range from 100 GHz to 10 THz, for potential applications in security scanning, atmospheric monitoring, medical imaging and ultrafast wireless communications [1]. The waveguide is usually a hollow air-filled tube used to confine and propagate electromagnetic waves, and is widely used at these terahertz frequencies. This is mainly due to its low loss characteristic (a low loss corresponds to a high transmission rate, i.e. a better performance). Conventionally, the waveguides are produced from metal through precisely controlled CNC milling. However, as the frequency continues to increase and the waveguide inner dimensions continues to decrease (e.g. cross section of the WR-3 waveguide discussed here is 864 µm × 432 µm), it is becoming more and more difficult and expensive for traditional CNC milling to machine the waveguides. In certain cases, CNC milling may fail to produce the complicated structures required inside the waveguide. During the past few decades, many different manufacturing techniques have been proposed to cope with the demand for high-dimensional accuracy and good surface quality for terahertz waveguide devices. Among them three techniques have been found the most suitable and these are: Silicon Deep Reactive Ion Etching (DRIE) [2], LIGA-based thick layer electroplating [3] and SU8 or KMPR photoresist based fabrication [4]-[5]. Waveguides produced using these techniques are usually built from several Si or SU8 layers that are then metalized to achieve a good electrical conductivity. Finally, the layers have to be assembled with high accuracy to form the waveguide devices. WR-3 waveguide devices made from SU8 had demonstrated a performance which was comparable to that produced by a high precision CNC milling from copper workpiece [4].

This research presents a design of a THz waveguide filter for hybrid manufacturing. In particular, the design utilises the milling technology to produce the meso scale waveguide features such as assembly holes for alignment and fixing to a flange, as shown in Fig. 1 (a), with a higher material removal rate and thus cost effectively. These features are only used as mechanical supporting structures and are not directly affecting the device's microwave functionality. At the same time the design utilises laser micro-machining to produce micro structures with dimensional accuracy better than 10 µm. Also this precision machining step uses alignment marks on the workpiece to carry out two-side processing in one setup with the necessary accuracy [6]. In this way, the critical functional features of the waveguide devices are laser micro-machined to achieve a higher resolution, feature sizes down to 100 µm, with a higher dimensional accuracy. In comparison with the SU8 process, the proposed design for hybrid manufacturing has three main advantages:

(i) The whole device can be machined from a workpiece with a good electrical conductivity. This is ideally suited to scenarios where a higher thermal stability of the devices is required;
(ii) The proposed hybrid approach is capable of producing 3D waveguide structures with variable depths from one workpiece and thus eliminates the need for splitting the device into several layers and then assembling them with a high accuracy. This could yield an improved insertion loss and

ultimately a better performance;

(iii) It is a direct write approach and small to medium size batches of devices can be produce cost effectively while there is a higher flexibility to introduce modification in the design.

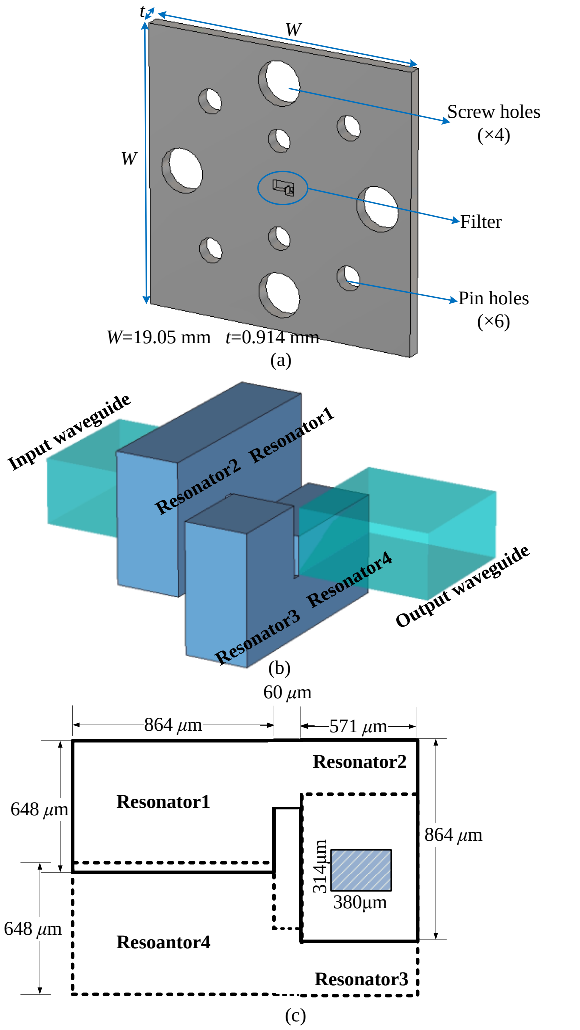


Fig. 1 Illustration of the WR-3 filter based on 4 coupled resonators: (a) Overview of the filter including holes for flange screws and pins; (b) The filter structure where the dark blue represents air inside the real device. Input /Output waveguides are not parts of the filter; (c) Front view of the filter. Blue color filled area stands for the coupling slot between Resonators 2 and 3.

A waveguide filter based on 4 coupled resonators was designed by following a procedure described in [7] to utilize the capabilities of this hybrid manufacturing approach. The filter allows the transmission of only certain frequencies (in the passband) to pass and reject the rest. Filters are crucial components in a microwave system to remove interference. Fig. 1 shows the configuration of 4th order filter operating at WR-3 band (220-325 GHz). The filter is based on a single piece of metal and therefore is expected to have an excellent insertion loss as there are no joints in the structure.

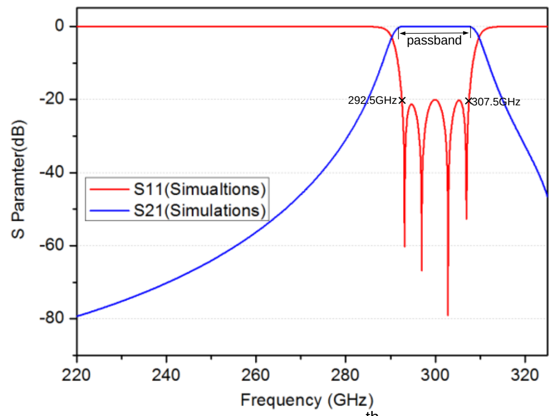


Fig. 2 Simulation results of the 4th order filter. Within the passband (292.5-307.5 GHz), the transmission rate is nearly 100%. This corresponds to 0 dB.

Usually, the scattering matrix is utilised to describe the microwave characterises of a waveguide device and the S-parameters are acquired directly in microwave measurements. S-parameters are generally used to present the transmission (S21) and reflection (S11) from a two-port microwave component and are usually expressed as decibels (dB). For a waveguide device, with the two ports numbered as ports 1 and 2, S11 describes the reflection coefficient or return loss, i.e. how much signal is reflected back to port 1 when port 2 is terminated with a matched load. The parameter S21 is the transmission coefficient the devices referenced from port 1 to port 2. Frequencies in a filter's pass-band are expected to be fully transmitted from port 1 to port 2 (i.e. have a transmission coefficient of 100% or 0 dB), whereas other frequencies are partially or fully reflected by the filter. Fig. 2 shows the simulation results of the 4th order filter designed for this work. It can be observed that S21 is around 0 dB over the passband frequency range from 292.5 to 307.5 GHz.

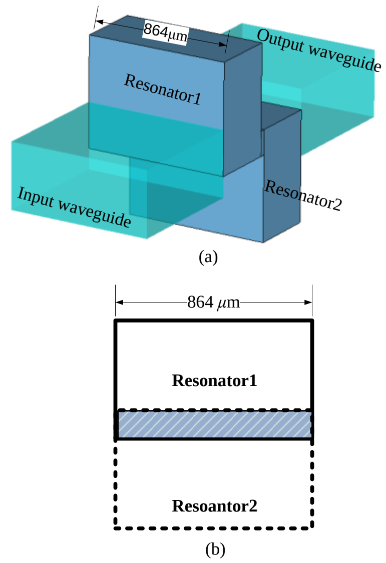


Fig. 3 Illustration of the 2nd order waveguide structure (simplified version of the filter shown in Fig. 1).

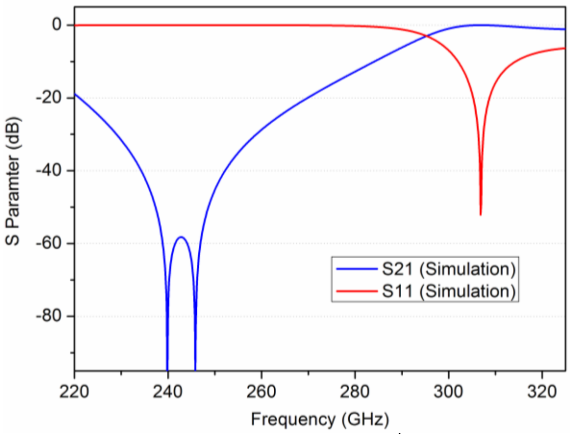


Fig. 4 Simulation results of the 2nd order filter (as shown in Fig. 3).

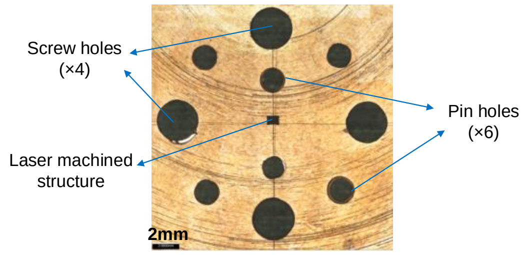
However, to carry out the design for manufacture analysis, a simplified version of the 4th order filter with only two resonators and one internal coupling was used. Nevertheless, the functional tests carried out on this simplified filter can be used to identify potential issues in producing the WR-3 4th order filter. The design of the WR-3 2nd order filter is shown in Fig. 3. It was produced employing the considered hybrid manufacturing route. Fig. 4 shows the simulation results of the simplified filter.

2. Pilot fabrication

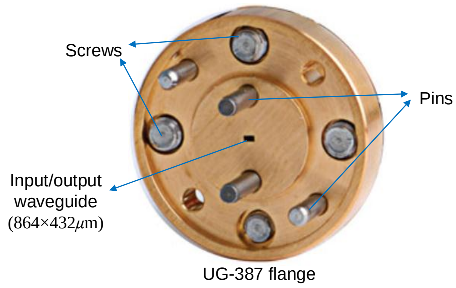
Fig. 5 shows the fabricated filter and the configuration of its corresponding UG-387 flange on the measurement system. The hybrid manufacturing approach was implements on a CNC turning machine and a multi-axes laser micro machining system that integrates Yb-doped sub-pico laser source with a wavelength of 1030 nm. Briefly the fabrication process included the following steps:

(i) Drilling the flanges fixing and alignment holes into a copper round bar with a diameter 50.8 mm with a good machinability and then cutting from it disks with the desired thickness on a CNC turning machine;
(ii) Fixing the disks on a pallet for the follow up two-side machining within one setup on the laser micro machining system;
(iii) Laser machining one-side of the filter structure by using an optimized beam path to produce vertical sidewalls (~90°).
(iv) Laser machining of a mark for a higher precision alignment of the filter structures produced on the two sides of the disk;
(v) Repositioning the pallet at 180° using the rotary axis of the system and then setting up new machining coordinate systems by using a alignment mark produced at step (iv);
(vi) Laser machining the filter structure by repeating step (iii).

More details about the fabrication process are given in [8].



(a)



(b)

Fig. 5 (a) Photo of the WR-3 2nd order filter; (b) Configuration of the UG-387 waveguide flange.

3. Measurements and discussions

The measurements were performed on an Agilent E8361A Network Analyzer with a pair of OML WR-3 extensions, as shown in Fig. 6. During the measurement, the filter was sandwiched between flanges of two test ports. Four alignment pins were carefully pushed through the waveguide filter and the flanges to reduce any misalignment between them. Screws attached to the flanges went through the waveguide device and into thread holes on the opposite flange to provide secured and intimate connections.

Fig. 7 shows the measurement results of the simplified filter, which are in good agreement with simulations. The simulation results are obtained using the measured dimensions of the fabricated filter. The measured best insertion loss is 1.6 dB, which is considerably higher than 0.05 dB obtained from the simulations using the conductivity of copper. In additional, the measured response curves deviate slightly from the targeted simulated ones. These deviations can be attributed to the following factors:

(i) The non-ideal copper disk flatness. This could lead to air gaps (energy leakage) at the interfaces between the filter and waveguide flanges of the measurement system. To address this problem, all unnecessary contact areas that could hinder the good contact between the functional contact surfaces should be removed. This can be achieved by offsetting the surfaces by around 100 μm and thus to minimise any uncertainties due to the filter-flange interface. Polishing can also be considered but it will improve only the surface finish while at the same time reduce the geometrical accuracy.
(ii) Reduction in copper conductivity due to oxidation or annealing during laser processing. A lower conductivity leads to a higher loss. To eliminate the impact of this factor, the filter could be coated with 2-3 μm thick silver or gold through evaporation. It is common to coat the microwave

devices, in particular terahertz ones, with gold or silver, in order to achieve a good electric conductivity.

(iii) Significant surface roughness which degrades the effective conductivity of copper. Silicon wafers are less reflective to laser beam and can be utilised to produce filters with a better surface roughness. However, there will be a need for a follow up metallisation step to achieve the necessary electrical conductive.

(iv) Small errors in filter dimensions and alignments between filter and flanges of test equipment. This leads to a degradation of filter performance in particular for S11 responses. Laser parameters need to be further optimised to provide a higher dimensional accuracy. The alignment between filter and test equipment relies on pins (see Fig. 5). Pin holes on the filter can be neither too large (poor alignment) nor too small (pins cannot fit in). A proper value needs to be obtained based on trial-and-error and then more precise alignment could be achieved.

All the above factors are still under investigation in this work and their impacts on the microwave performance are being analysed. Further tests will be conducted to quantify their effects.

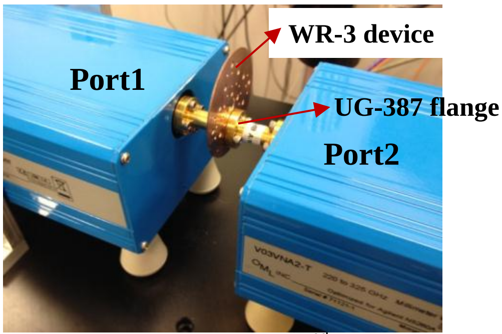


Fig. 6 Measurement setup for the 2nd order filter.

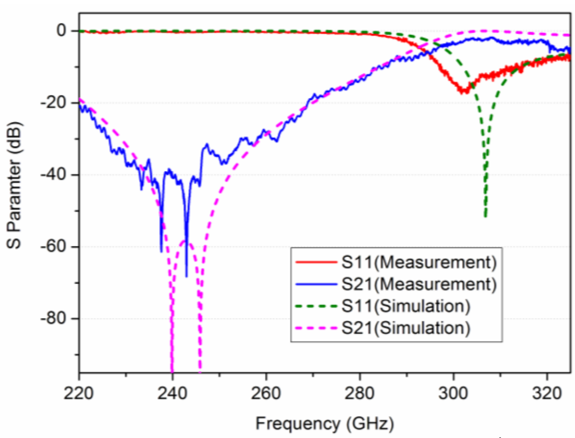


Fig. 7 Measurement results of the WR-3 2nd order filter. Simulation results (using measured dimensions of the fabricated filter) are included for comparison.

4. Conclusions

WR-3 waveguide filters was designed for investigating a hybrid manufacturing approach that combines the capabilities of CNC mechanical machining and laser micro structuring. In particular, a simplified WR-3 filter based on two resonators was used to carry out the design for manufacture analysis in regards to achievable dimensional accuracy and surface integrity and their impact on the waveguide performance when hybrid manufacturing is utilized. The good agreement between measurement and simulation results that was achieved demonstrates the potential of the proposed design for producing low-cost THz waveguide devices. The laser machining time was less than 4 minutes and this make the hybrid manufacturing route viable for producing small to medium batch sizes of THz waveguide devices while offering a higher flexibility for design changes. Additionally, the design allows 3D filter designs to be produced from a single copper workpiece (i.e. no need of a precision alignment and joining of multiple layers) with good thermal stability and electrical conductivity for improved device performance.

The work is ongoing to optimize concurrently the design of THz waveguide filters together with the considered hybrid manufacturing platform and thus to address some open issues affecting the device performance.

Acknowledgements

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